Analysis of the Physical Phenomena and Modelling Procedures of Building Heating and Cooling Emission System Energy Losses

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Abstract. An important research issue in assessing the energy performance of buildings concerns the modelling of the interaction between the built environment and the heating/cooling emission systems. Several methods can be used to evaluate the effect of the heating emitter characteristics, including the possible embedment in the building structure, non-uniform space temperature distribution, and the accuracy of the indoor temperature control. Generally, technical standards specify simplified, yet insufficiently validated methods, based on tabulated values. This paper outlines the main simplified procedures for assessing the efficiency of the emission subsystem, with a particular focus on the hydronic systems. It describes the essential datasets required for the analysis and highlights the interaction with phenomena related to the emitter heat loss. The simplified calculation procedures are then methodologically compared with detailed simulation tools, such as EnergyPlus, to identify differences and limitations in the models. The main discrepancies in the procedures and the required input data are highlighted, and possible strategies for improving the simplified methods are presented. A building representative of the European residential building stock is then analysed in the Italian climate using different calculation procedures. The results, in terms of thermal output of the emitter, are then analysed and compared.

1 Introduction

The emission subsystem has a significant impact on the energy performance of a building. For this reason, it is of utmost relevance to have calculation procedures that can accurately predict and assess the performance of these components. The losses related to the emission system are significantly connected with the control system, as well as with the building and its users. Modelling the phenomena related to these interactions is challenging and requires a significant amount of detailed information. While there are currently high-precision procedures available, their complexity makes them less suitable for widespread application. Therefore, it is crucial to develop, analyse and validate simplified procedures that can leverage the trade-off between simplicity and accuracy.

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In the last years, several procedures for enhancing building energy efficiency at the European level have been updated, driven by the normative updating implemented under Mandate M/480 EN [1]. Concerning the technical building systems for heating and cooling, several changes were actuated in order both to increase the accuracy of the procedures and to clarify their application. Regarding the emission terminals for heating and cooling and the control sub-system, this effort was not complete since the European standard EN 15316-2 [2] has reduced the number of calculation procedures to a single one compared to the withdrawn version [3]. The same issue can be also found worldwide since ISO 52031 [4] presented the same procedure as the European standard. This procedure, at the current moment, is lacking from different points of view since complete validation procedures are currently unavailable, and because the presented methodology is a mere application of tabulated values that do not allow a particular characterisation of the actual emission terminal influence.

Additional calculation procedures are available, often associated with detailed building energy assessment tools. These, while being able to properly consider the changes in the loads, often oversimplify the complexity associated with emission loss phenomena.

1.1 The energy losses within the emission system and underlying causes

The emission losses related to the building heat emitters and the related control system can be identified in two main categories, such as the spatial temperature variation due to the stratification, and the overheating of building components.

Temperature stratification happens when the air in the environment presents different temperatures across the considered space, creating distinct temperature layers in the air volume. This behaviour is related to several key factors. Firstly, air temperature discrepancies are related to the heat exchanges between the air and the objects that are in contact with the air mass. Heterogeneity in both spatial distribution and size of conduction and convection effects amplifies the stratification phenomena. This phenomenon is significant, for what concerns the emission terminals, when the component presents a high-temperature difference from the surrounding air. The spatial homogeneous distribution of the heat exchanges can be increased using high-surface radiant emitters or sufficiently distributed air vents, but cannot be completely achieved due to technical and economic reasons. Secondly, the thermal behaviour of air and the relation between temperature and density causes the air to be naturally arranged going from the lowest temperature to the highest one, from bottom to top. The last aspect is the air velocity, which can be influenced either by natural factors, such as a temperature variation, or by artificial ones, such as the presence of fans. The movement of air tends to mix the air, increasing the heat exchange between the air itself leading to a more uniform temperature.

Another significant phenomenon is the overheating of building components. This phenomenon occurs when the elements suffer an excessive heat exchange with the surrounding environment, internal or external. Typically, it can be caused by free gains, such as solar radiation, and it is influenced by the components' thermal mass and the heating system. This phenomenon is relevant for the emission terminals, especially for the components that convey a significant part of the heat through radiative heat exchange.

The factors influencing the losses in the emission and control sub-system can be classified into two groups of components, namely, the technical building system components and the building itself. If the focus is put on the emission/control components, the parameters can be categorised into two different sections:

- The emission terminal *type* - It is related to the emission terminal main category. It usually differs depending on the different shares of heat transfer method as well as from the deployed heat transfer fluid properties or the technical components that are included in the terminal.

• The emission terminal *model* - All the terminals that belong to the same type may differ from several points of view, such as the material, the shape, or the heating/cooling capacity.

The main analysed parameters for the emitters are presented in Annex A, Table A.1.

1.2 The state of the art in the modelling of emission and control system losses

Recent literature regarding the improvement simplified procedures to assess the energy efficiency of emission and control systems is quite limited. Regarding the efficiency of hydronic emission systems, first efforts were made by Maivel et al. [5] in the analysis of the procedures of EN 15316-2-1 [3] with a comparative analysis with detailed calculation procedures. Significant differences were found between the procedures, especially in the case of low-temperature emission systems. Other efforts in the comparative validation were performed by Maivel et al. [6] analysing the simplified standard procedure for radiators and floor heating systems against IDA-ICE. In this study, the influence on the efficiency of different emission systems, as well as the relation between building, emission and control system, was underlined and pointed out as one of the main causes of the analysed simplified procedure inaccuracies. Similar studies on the simplified procedure contained in EN 15316-2 [2], were developed by Maivel et al. [7] to evaluate the influence of stratification in the emission efficiency. The work, based on the comparison with empirical data as well as data derived from detailed analyses, confirmed the differences between methods, pointing out the influence of the control strategy in the determination of the emission losses. Other studies, such as Seifert et al. [8], explored the standard simplified procedures compared to empirical analyses, to assess the efficiency accuracy of the radiator and the thermostatic control valve.

The lack of standardised procedures to assess the parameters needed to perform the EN 15316-2 [2] procedure from an analytic point of view was pointed out and explored by Võsa et al. [9]. A method to be applied in place of the one provided by the standard was proposed to assess a temperature variation related to the emission losses.

While often studies, such as [10] and [11], focus on the thermal performance of emission terminals in terms of heat transfer quality, a complete and extensive analysis of the emission losses is still lacking.

1.3 Aim of the research

This research aims to address the existing knowledge gap regarding the validation of simplified calculation procedures for assessing the energy losses of heat emitters and control systems. The analysis is performed first from a theoretical point of view, involving the identification of key parameters related to the heat emitters, the control systems, and the building that influence the energy losses. The focus is then on the most recognised available simplified procedures for hydronic terminals. These methodologies are briefly outlined, alongside more detailed approaches, to underline differences in detail and computational complexity. A comparative analysis is then performed on a case study to highlight the deviations among different calculation procedures applied.

2 Calculation methods

In this section, the main parameters related to the emission terminals are analysed to underline the possible interaction between them and the energy losses related to the emitters. Then, the main procedures to assess these losses, or the component efficiency, for the hydronic emitters are presented. The analysis is focused on two main components, i.e., the radiator and the floor cooling/heating systems.

2.1 Building and system parameters and their influence on the emission system energy losses

As presented in Section 1.1, several properties influence the emission system energy losses. The main parameters are related to three groups: the emission system, the control system, and the zone properties. These are quite interconnected, and parameters are often co-dependent between each other. In Annex A, Table A.2, the main properties, along with the relevant unit of measure, are defined. This table is not supposed to be an exhaustive list of all the existing parameters that can be deployed during the assessment of the emission and control system losses. Rather it is meant to give an overall overview of the parameters that are commonly used to perform simplified and detailed calculation procedures regarding the emission system efficiency. Commonly, several of these parameters are not directly available on the component technical sheets. To solve this issue, the only feasible option is to use standard values that may or may not cause uncertainties in the results.

2.2 Calculation procedures – General (Simplified method)

The simplified procedure here analysed is presented in both EN 15316-2 [2] and ISO 52031 [4]. It determines, based on the component properties and the room properties, a difference in the internal temperature. The fictitious internal temperature derived from the sum of this calculated value with the original air temperature is then used to determine the losses through the envelope. The increase in energy consumption derived from this temperature variation is the energy loss related to the emission system.

This procedure, presented in Fig. 1, can deploy both product and fixed values, but since the first ones are not easily available, the tabular approach is often applied. The procedure considers the influence of both emission and control, but the two values can be determined separately. In addition, for each of these two groups other specific values can be determined; they are related to the temperature stratification, the presence of embedded emitters, the type of the emitter, the intermittent operation, the control variation, and the space automation. The balancing of hydraulic systems is also considered.

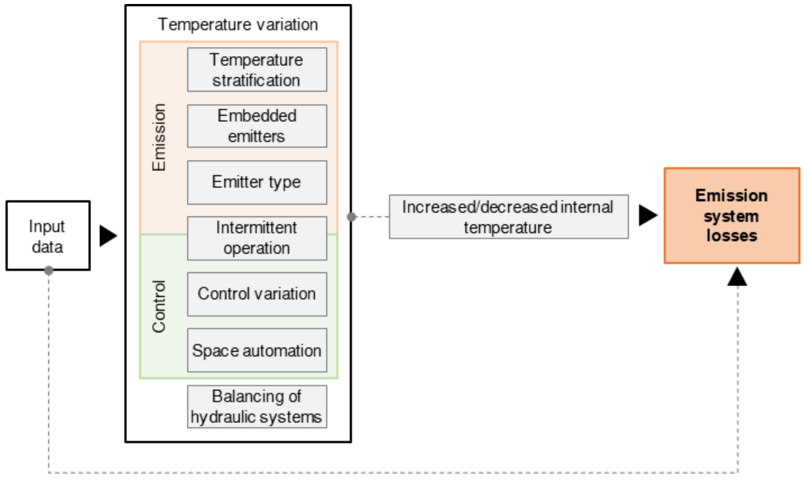

Fig. 1. Simplified model schema.

Fig. 2 presents the procedure to determine the input parameters [9]. This procedure deploys input data that are related to the specific emission terminal and the interaction between the terminal and the zone. Information regarding the air temperature stratification in the zone is required. The procedure compares the results of two mathematical models performed on the same calculation tool. The two models differ only for the emission and control subsystems. The first model, which can be defined as the baseline, presents an ideal terminal. All the heat transmission is considered convective, no stratification is involved, and the control system is regulated using the operative temperature. The second model, on the other hand, deploys the real terminal, and the control is performed on the air temperature. Using the baseline model, a curve that describes the correlation between set-point temperature and energy consumption is defined. The real model is used to determine the energy consumption related to the minimum air temperature set-point that can guarantee the required operative temperature for at least 95% of the considered time-steps. Using this energy consumption value and the previously described graph, the required temperature and, therefore, the temperature variation are determined.

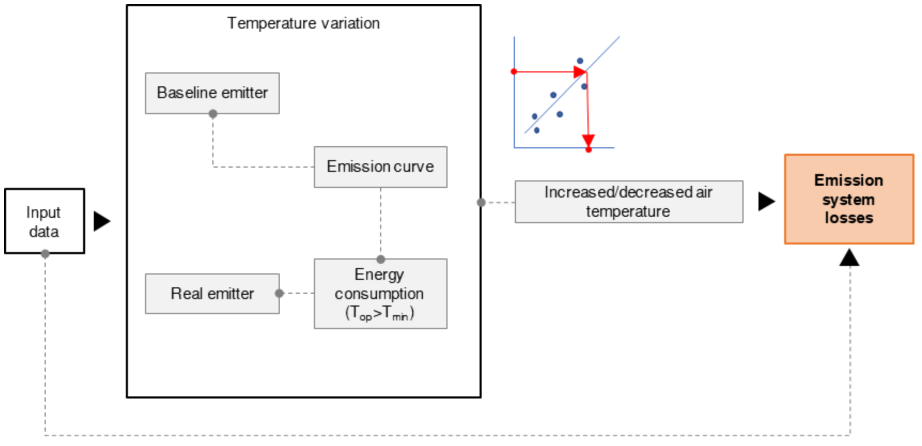

Fig. 2. Simplified model schema proposed by Võsa et al. [9].

2.3 Calculation procedures – Radiator (Detailed method)

The heat transmitted through convective heat transfer is directly considered to increase the air temperature, while the one transmitted through radiant heat transfer is distributed to the building components and the occupants. The radiation on the building components, which may not be distributed in a non-homogeneous way, has the main effect of increasing their temperature, while the fraction on the occupants is considered again directly transferred to the zone, increasing the air temperature. The control of the emission terminal is regulated through a zone thermostat that typically considers either the air temperature or the operative temperature. The control accuracy is dependent on the calculation time-step and can differ depending on strategies, such as the on/off and the proportional one. While being quite straightforward, this procedure does not consider and directly evaluate the temperature stratification, which can be partially assessed by implementing user-defined temperature distribution through the heated space. In such a way, it is possible to determine the effect of a predetermined scenario, but it is not possible to evaluate the actual influence of the various parameters that affect the stratification, or how the phenomenon changes over time.

2.4 Calculation procedures – Low-temperature radiant system (Detailed method))

One of the possibilities to model the effect of low-temperature radiant systems is to directly consider the temperature variation in the building component. The position of the radiant emitter inside the building component is defined to evaluate the relevant inertia and thermal resistance of the layers around the heat exchanger. This procedure can be found in simulation tools such as TRNSYS (directly embedded in type 56), or EnergyPlus. This approach can be followed using the State Space formulation. The control of the emission terminal is regulated through a zone thermostat. In this specific case, due to the inertia of the components, a refined control system may be required to properly match the fluctuations of both the energy need for heating and the low-temperature radiant system heat output. As for the radiator, simplified stratification scenarios can be considered.

3 Application

3.1 Case study

The analysed building is the European reference room defined in ISO 52031-1 [4]. The room is a 20 m^2 floor residential space with one wall adjacent to the external environment, South-oriented. On the same wall, there are two windows. All the other envelope sides are adjacent to spaces heated at the same temperature, therefore considered as adiabatic for heat exchange purposes. The opaque vertical components, both internal and external, are made of bricks with different thicknesses. The horizontal components are concrete slabs with parquetry as finishing. The two windows have a wooden frame and are composed of two glass panes with air in the gap. The main properties of the envelope components are presented in Table 1.

Table 1. Properties of the building components.

Component	Useful floor area [m^2]	Thermal transmittance [$W\ m^{-2}\ K^{-1}$]	Thickness [m]	Areal internal heat capacity [$kJ\ m^{-2}\ K^{-1}$]
External wall (South)	9,5	0,90	0,40	48,2
Internal wall (North)	12,5	2,38	0,15	58,9
Internal wall (West/East)	10,0	2,38	0,15	58,9
Ceiling	20,0	2,77	0,19	49,1
Floor	20,0	2,32	0,19	88,0
Window	1,5	2,34	-	-

The room is ventilated with natural ventilation with an airflow rate of 1 h^{-1}. A set-point of 20 °C for heating was considered. The building is analysed using the typical meteorological year for the city of Milan, Italy. The building occupancy, lighting, and appliances schedule as well as the related heat emissions are derived from international standards [12].

Two emission scenarios were analysed. The first one is composed of a radiator, whose dimensions are 1,15 m in length, 0,85 m in height, and 0,10 m in width. A radiative factor equal to 0,3 was considered. The second one is a low-temperature surface heater integrated into vertical or horizontal envelope components depending on the considered case.

3.2 Workflow

Different procedures were analysed and compared. In particular, the procedure presented in Section 2.2 was compared with the procedures presented in Sections 2.3 and 2.4, in the latter case using EnergyPlus [13]. The case study was analysed considering two different emission terminals, a radiator and a low-temperature surface heater, in different configurations, as presented in Table 2. Every considered case study code is determined as follows. The first letter represents the considered terminal, i.e., radiator (R), or low-temperature surface heater (L). The second letter represents the applied calculation procedure, either the detailed one (E) or the simplified one (S). The last number, from one to three, represents the considered position in the room.

Table 2. Properties of the building components.

Component	Position	Code	
		EnergyPlus	Standard procedure
Radiator	External wall	R-E-1	R-S-1
	Internal wall (West)	R-E-2	R-S-2
	Internal wall (North)	R-E-3	R-S-2
Low-temperature radiant heater	Floor	L-E-1	L-S-1
	Ceiling	L-E-2	L-S-2
	Wall	L-E-3	L-S-3

The results are provided in terms of thermal output of the heating emission system normalised on the floor area. The study only considers the effect of the type of emission system, neglecting the effect of the stratification and assuming a control system close to an ideal one. For the standard case, a fully convective system was deployed, and only the parameters related to the emission type and the component position were considered. The energy assessment of the case studies was performed using EnergyPlus, according to the respective emission terminal calculation procedure.

4 Results and discussion

The analysis of the results showed significant differences between the methods. Fig. 3 shows the main results of the conducted analysis. The months out of the heating season were neglected. The first run of simulation shows a noticeable difference in the results of the low-temperature radiant system analysed with the detailed procedure, compared with all the others. The hourly results show that the assumed control system is not able to properly modulate the heat output, leading to overheating phenomena and to an increase in the energy consumption of the system. The set-point temperature in these cases was then modulated to reach, at least in 95 % of time-steps, the required set-point temperature. This procedure only reduced the overheating issues, while maintaining high thermal output values compared to the other cases.

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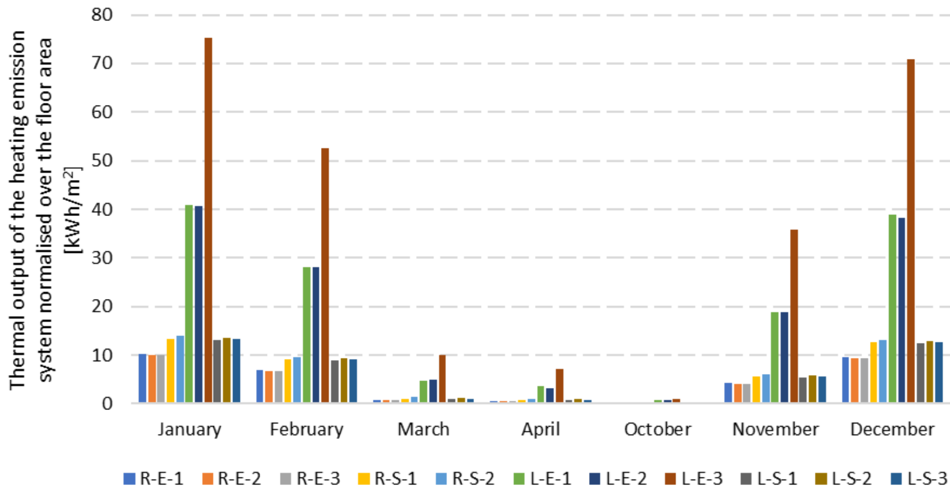

Fig. 3. Thermal output of the heating emission system normalised over the floor area.

Fig. 4 shows the mean bias error (MBE) and the coefficient of variation of the root mean square error (cv(RMSE)) of the thermal output between the standard and the detailed method. In both cases, the detailed procedure is considered as the reference set of data.

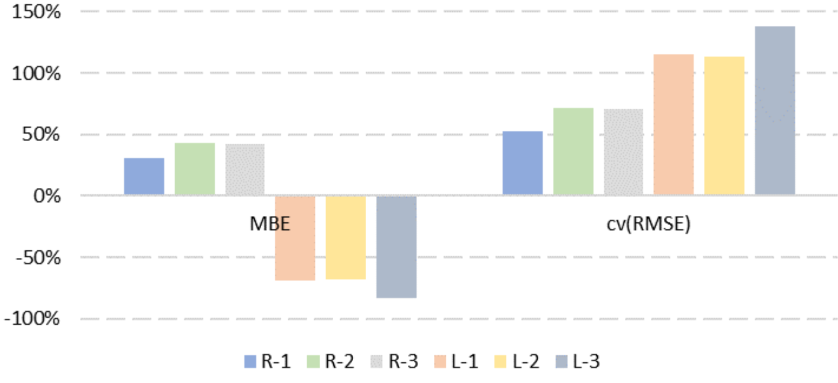

Fig. 4. MBE and cv(RMSE) of thermal output of the heating emission system between standard and detailed method.

Statistical indicators highlight not negligible differences between the methods. Several of these are related to the application of the standard procedure. The operative temperature used as set-point is determined as the mean between the air temperature and the mean radiant temperature of the components enclosing the zone. The use of this temperature as the parameter for the thermostat sensor influences the relevance of both radiant and convective fractions of the heating emitter. In the considered case, it is noticeable that a significant difference can be detected in the comparison between a fully convective system and a system with 70 % of convective fraction. For this reason, it is quite relevant to properly define both the share and the distribution of the radiant fraction. The variations between the considered scenarios for both the radiator and the low-temperature radiant system constitute a minor part, yet they highlight significant discrepancies in the outcomes.

5 Conclusions

The present work analyses the phenomenon of energy losses related to the heat emission system of a building and the procedures for assessing these losses. Two primary energy loss categories, namely temperature stratification and overheating of building components, were identified, and the main phenomena associated with them were described. An analysis of properties related to the emission system considered the interconnection between the terminal, the building, and the control system. For each analysed property, a group of parameters capable of describing the components that can be deployed in calculation procedures was defined.

Different calculation procedures, distinct in the level of detail and required input data, were studied for the assessment of the heat emitter losses. The analysis highlighted the shortcomings in current simplified methods, either in properly considering all the involved phenomena or in being transparent and flexible in application. A comparative analysis was performed on two types of calculation procedures - a standard one and a detailed one. The case study involved a building with standard geometry and thermal properties in an Italian climate. Results highlighted non-negligible differences between the procedures that can be attributed to differences in convection factors and considered inertia.

This work focused mainly on the analysis of the differences between calculation procedures for the assessment of the losses of the thermal emission system. Future research could also benefit from deploying experimental data to define a hierarchy between the analysed methods, as well as to evaluate the suitability of the different procedures depending on the considered scenario. Additionally, it would be significantly useful to deploy other indicators, such as those related to the whole building performance or thermal comfort, to define the impact of the studied procedures from a wider perspective.

Future studies should also focus on analysing additional phenomena related to emission losses, especially air temperature stratification. The current existing methods, based on CFD analyses, are still not suited for an extensive application due to the complexity of the input data and the required simulation time.

The results also underline the relevance of the control systems in assessing the energy losses in the emission system. Future studies could explore the influence of different control strategies, comparing existing calculation procedures.

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Annex A

This annex reports the main properties of the emission terminals, focusing on their influence in the determination of the specific component, and presenting parameters that can be deployed to describe them.

Table A1. Properties of the emission terminals – general aspects.

Property	Energy performance relation	Dependence on emitter type	Dependence on emitter model
Geometry, shape, and material	Yes	Yes	Yes
Position	Yes	Yes	No
Size (referred to thermal output)	Yes	No	Yes
Type of heat transfer	Yes	Yes	No
Heat transfer fluid properties	Yes	Yes	No
Heat transfer conditions	Yes	Yes	Yes
Presence of heat generation	Yes	Yes	No
Presence of heat exchangers	Yes	Yes	No
Supply air origin	Yes	Yes	Yes
Presence of fans	Yes	Yes	No

Table A2. Properties of the emission terminals and control systems, and their relationship with the thermal zone – Parameters and units of measure.

System	Property	Parameter	Unit of measure	Relevant standard
E	Geometry, shape, and materials	Height	m	[14]
		Length	m	[14]
		Depth	m	[14]
		Heating/cooling surface*	m^2	[14]

System	Property	Parameter	Unit of measure	Relevant standard
		Dry mass	kg	[14]
		Water content	m^3	[14]
		Internal/external diameter of the pipe*	m	[15]
		Pipe spacing*	m	[15]
		Length of installed pipes*	m	[15]
		Thermal resistance	$m^2\ K\ W^{-1}$	[16]
		Response time	min	[17]
		Emissivity	-	[16]
E	Emitter position	Position of heat-exchange surfaces in the room	m	[15]
		View factors between the terminal and the zone building components	-	[15]
E	Size (referred to thermal output)	Thermal output	W	[16]
E	Type of heat transfer	Percentage of radiant heat output	%	[18]
E	Heat transfer fluid properties	Type of fluid (hot water, chilled water, air, etc.)	-	-
		Density	$kg\ m^{-3}$	[19]
		Specific heat capacity	$J\ kg^{-1}\ K^{-1}$	[16]
E	Heat transfer conditions	Inlet temperature	°C	[16]
		Outlet temperature	°C	[16]
		Flow rate	$kg\ s^{-1}$	[16]
		Pressure	kPa	[16]
E	Fan(s) features	Rotational speed of the fan(s)**	s^{-1}	[20]
		Electrical power of the fans(s)**	W	[21]
		Air velocity	$m\ s^{-1}$	[15]
E	Produced noise	Sound power level	dB	[22]
C	Control system position	Sensor position	m	-
C	Control system type	Variable measured by the sensor (e.g., air temperature, operative temperature, etc.)	-	-
		Operation and controller type (e.g., intermittent, continuous, proportional, proportional-integrative, etc.)	-	-
Z	Adjacent component(s) properties and boundary conditions	Type of space on the other side of the partition (e.g., another zone, the external environment)		
		Thermal resistance	$m^2\ K\ W^{-1}$	
Z	Embedding construction properties and boundary conditions	Type of space on the other side of the construction (e.g., another zone, the external environment)	-	-

System	Property	Parameter	Unit of measure	Relevant standard
	(in case of embedded emitter)	Partial inwards/outwards thermal resistance of the surface structure*	$m^2\ K\ W^{-1}$	[23]
		Specific heat capacity of the emission system	$kJ\ m^{-2}\ K^{-1}$	[24]
E = emission system, C = control system, Z = zone * only for embedded emitters, ** only for emitters that deploy air as heat transfer fluid				